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MULTI-PARAMETER INTERFEROMETRIC FIBER OPTIC SENSOR

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CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit under 35 USC §119 of the filing date of PCT
15 Application No. PCT/US00/30901, filed November 10, 2000, the disclosure of which is incorporated herein by this reference.

BACKGROUND

20   The present invention relates generally to fiber optic sensors and, in an embodiment described herein, more particularly provides a method of sensing multiple parameters in a well using a single sensor.

Pressure signals have been measured in subterranean wells for many years. These pressure signals may be relatively low frequency, such as pressures monitored
25   during production logging, drill stem testing, well monitoring, etc. These pressures

change relatively slowly. Other pressure signals are relatively high frequency, such as pressure signals used in acoustic telemetry, etc., which may have frequencies from many hertz to many kilohertz.

5   Present sensors used for measuring these pressure signals are typically designed for measuring only low frequency signals or only high frequency signals. If it is desired to measure both low frequency and high frequency signals, then at least two sensors must be used. This circumstance occurs, for example, in operations where acoustic telemetry is used for communication and pressure transducers are used for monitoring well pressure in the same operation.

10   It would, therefore, be advantageous to be able to use a single sensor to measure multiple parameters, such as low and high frequency pressure signals.

SUMMARY

15   In carrying out the principles of the present invention, in accordance with an embodiment thereof, a method of sensing multiple parameters is provided which solves the above problem in the art. A fiber optic sensor system is also provided for use in the method.

In one aspect of the invention, a relatively low frequency signal is measured 20   by transmitting light from a light source through a fiber optic sensor. The light is swept over a range of wavelengths. A relatively high frequency signal is also measured by transmitting light from the light source through the sensor at a constant wavelength.

In another aspect of the invention, the light source is a tunable laser and the 25   fiber optic sensor is an interferometric sensor, for example, using a Mach-Zehnder or Michelson interferometer. The sensor has two optical paths. One of the optical paths changes in length in response to a change in a signal, such as pressure, applied to the sensor.

In a further aspect of the invention, an optical output of the sensor is input to a computer via an opto-electric converter. The computer controls the wavelength output of the light source.

In yet another aspect of the invention, multiple sensors may be connected to the light source to measure signals at each of the sensors.

These and other features, advantages, benefits and objects of the present invention will become apparent to one of ordinary skill in the art upon careful consideration of the detailed description of a representative embodiment of the invention hereinbelow and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of a method embodying principles of the present invention;

FIG. 2 is a schematic block diagram of a fiber optic sensor system embodying principles of the present invention, and which may be used in the method of FIG. 1; and

FIG. 3 is a schematic block diagram of another fiber optic sensor system embodying principles of the present invention, and which may be used in the method of FIG. 1.

DETAILED DESCRIPTION

Representatively illustrated in FIG. 1 is a method 10 which embodies principles of the present invention. In the following description of the method 10 and other apparatus and methods described herein, directional terms, such as "above", "below", "upper", "lower", etc., are used only for convenience in referring to

the accompanying drawings. Additionally, it is to be understood that the various embodiments of the present invention described herein may be utilized in various orientations, such as inclined, inverted, horizontal, vertical, etc., and in various configurations, without departing from the principles of the present invention.

5   In the method 10, fiber optic lines 12 are connected to interferometric sensors 14, 16 positioned in a subterranean well. Only two of the sensors 14, 16 are depicted in FIG. 1 as being conveyed into the well as part of a tubing string 18, but it is to be clearly understood that the sensors could be otherwise conveyed and positioned in the well, and any number of sensors could be used, without departing from the 10   principles of the present invention.

The sensors 14, 16 are used in the method 10 to sense multiple parameters, such as both relatively low frequency and relatively high frequency pressure signals at each sensor. The sensors 14, 16 may be distributed within the well at any locations where it is desired to measure these parameters. It is to be clearly understood, 15   however, that the principles of the invention are not limited to measuring pressure signals. Other types of signals may be measured using interferometric sensors. As used herein, the term "signal" encompasses any variable parameter which may be measured. For example, changes in temperature may be measured using interferometric sensors, in keeping with the principles of the present invention.

20   Referring additionally now to FIG. 2, a fiber optic sensor system 20 embodying principles of the present invention is schematically and representatively illustrated. The sensor system 20 may be used in the method 10 of FIG. 1. Thus, elements of the sensor system 20 which are similar to those previously described are indicated in FIG. 2 using the same reference numbers.

25   Only one sensor 14 is depicted in FIG. 2 for illustrative clarity, However, it is to be understood that any number of sensors may be used in the sensor system 20, for measuring relatively low and relatively high pressure signals at each sensor.

The sensor 14 in the sensor system 20 is depicted in FIG. 2 as including a Mach-Zehnder interferometer, well known to those skilled in the art. The sensor 14

has two optical paths 22, 24 extending between two optical couplers 26, 28. An optical path length of the path 22 changes in response to a change in pressure applied to the sensor 14. For example, the path 22 may be attached to a structure, such as a cylinder or membrane, etc., which experiences a strain when pressure is applied thereto. A change of strain in the structure produces an associated change of optical path length for the path 22.

Light is transmitted through the sensor 14 by means of a light source, such as a tunable laser 30, which may have an isolator 32 associated therewith. Light from the laser 30 is transmitted through one of the fiber optic lines 12 to the coupler 28, where it is split between the two paths 22, 24. After traversing the paths 22, 24, the light is recombined in the coupler 26.

The amplitude of the light output from the coupler 26 depends upon the relationship between the phases of the light received from the paths 22, 24 at the coupler 26. The relative phases of the light received from the paths 22, 24 depends upon the difference in optical path lengths. Therefore, the amplitude of the light output from the coupler 26 may be related to the pressure applied to the sensor 14.

Note that the above description of the sensor 14 is based on the sensor being provided as a Mach-Zehnder sensor. It is, however, to be clearly understood that other types of sensors may be utilized. For example, the sensor 14 may be a Michelson, Fabry-Perot, or other type of sensor.

The light output from the coupler 26 is transmitted via another of the fiber optic lines 12 to an opto-electric converter 34, such as a photodiode or photo voltaic device, etc. The converter 34 converts the optical signal output from the sensor 14 to an electrical signal for input to a computer 36. The computer 36 may be used to analyze the sensor 14 output and to control the laser 30.

When it is desired to measure a relatively low frequency pressure signal with the sensor 14, the computer 36 directs the laser 30 to transmit light having a sweep of wavelengths through the sensor. The amplitude of the optical output of the sensor 14 is dependent upon the wavelength of the light transmitted through the sensor and

the pressure applied to the sensor. The computer 36 determines the relationship between the sensor 14 optical output and the swept range of wavelengths, that is, the optical output amplitude as a function of wavelength, thereby enabling a calculation of the pressure applied to the sensor.

When it is desired to measure a relatively high frequency pressure signal with the sensor 14, the computer directs the laser 30 to transmit light having a constant wavelength through the sensor. The optical output of the sensor 14 varies in frequency and amplitude in response to the varied frequency and amplitude of the pressure signal applied to the sensor. The computer 36 may be used to interpret and/or store the sensor output.

Note that the computer 36 may be used to direct the laser 30 to alternately transmit wavelength sweeps and a constant wavelength through the sensor 14, in order to alternately sense low frequency and high frequency pressure signals. However, it is to be clearly understood that it is not necessary for a wavelength sweep transmission to be followed by a constant wavelength transmission, or vice versa, since a wavelength sweep transmission may be performed at any time it is desired to measure a low frequency pressure signal and a constant wavelength transmission may be performed at any time it is desired to measure a high frequency pressure signal.

Referring additionally now to FIG. 3, a fiber optic sensor system 40 embodying principles of the present invention is schematically and representatively illustrated. The sensor system 40 may be used in the method 10 of FIG. 1. The sensor system 40 is similar in many respects to the sensor system 20 described above, but differs in at least one respect in that it utilizes a Michelson interferometer in a sensor to measure multiple parameters. Elements of the sensor system 40 which are similar to those previously described are indicated in FIG. 3 using the same reference numbers.

Only one sensor 14 is depicted in FIG. 3 for illustrative clarity, However, it is to be understood that any number of sensors may be used in the sensor system 40, for measuring relatively low and relatively high pressure signals at each sensor.

The sensor 14 in the sensor system 40 is depicted in FIG. 3 as including a
5 Michelson interferometer, well known to those skilled in the art. The sensor 14 has two optical paths 42, 44 extending between an optical coupler 46 and mirrors 48, 50 at ends of the respective paths. An optical path length of the path 42 changes in response to a change in pressure applied to the sensor 14. For example, the path 42 may be attached to a structure, such as a cylinder or membrane, etc., which
10 experiences a strain when pressure is applied thereto. A change of strain in the structure produces an associated change of optical path length for the path 42.

Light is transmitted through the sensor 14 by means of a light source, such as the tunable laser 30, which may have the isolator 32 associated therewith. Light from the laser 30 is transmitted through one of the fiber optic lines 12 to the coupler
15 46, where it is split between the two paths 42, 44. After traversing the paths 42, 44, being reflected by the mirrors 48, 50, and again traversing the paths in an opposite direction, the light is recombined in the coupler 46.

The amplitude of the light output from the coupler 46 depends upon the relationship between the phases of the light received from the paths 42, 44 at the
20 coupler 46. The relative phases of the light received from the paths 42, 44 depends upon the difference in optical path lengths. Therefore, the amplitude of the light output from the coupler 46 may be related to the pressure applied to the sensor 14.

The light output from the coupler 46 is transmitted via another of the fiber optic lines 12 to the opto-electric converter 34, which converts the optical signal
25 output from the sensor 14 to an electrical signal for input to a computer 36. The computer 36 may be used to analyze the sensor 14 output and to control the laser 30, as described above, for measuring relatively low frequency and relatively high frequency pressure signals.

Of course, a person skilled in the art would, upon a careful consideration of the above description of representative embodiments of the invention, readily appreciate that many modifications, additions, substitutions, deletions, and other changes may be made to the specific embodiments, and such changes are contemplated by the principles of the present invention. Accordingly, the foregoing detailed description is to be clearly understood as being given by way of illustration and example only, the spirit and scope of the present invention being limited solely by the appended claims.